

## Solute Fluxes in Meltwaters Draining from a Glaciated Basin in the Karakoram Mountains

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### ABSTRACT

Electrical conductivity of meltwaters in the Batura River, which drains from the portal of Batura Glacier in the Karakoram Mountains, was recorded continuously, together with stage, throughout an ablation season with the aim of estimating the annual total solute flux from the 56% glacier-covered basin. Through-time variations of meltwater cationic concentration were obtained from the electrical conductivity record using a rating curve established between sums of cations determined in periodically collected samples of meltwater and electrical conductivity measured at the times of sampling. Hourly average cationic flux was then obtained as the product of cationic concentration and discharge, error arising as a result of inaccuracy in river gauging and use of the rating relationship. Electrical conductivity varied diurnally inversely with discharge, overall level decreasing as discharge increased in spring, continuing subdued through July and August irrespective of episodic discharge fluctuations. In contrast, solute flux mimicked discharge variation, low solute concentrations being offset by the volume of water flowing. Total annual cationic flux from Batura basin was  $1.03 \text{ Meq} \pm \sim 15 \text{ per cent}$ . Assuming almost all of the flux was derived subglacially, the solute flux from beneath Batura Glacier was  $2.64 \pm 0.40 \text{ eq m}^{-2} \text{ a}^{-1}$ . These rates of cationic denudation, substantially higher than the continental average, are at the top end of the global range of reasonably reliable estimates for other smaller glaciated basins. Carbonate lithology, high annual runoff, high sediment concentration in meltwaters, and long subglacial pathways account for the high solute flux from Batura Glacier. Through longer residence times of meltwater in transit under ice and higher discharges, dissolution kinetics and flow couple to enhance solute fluxes from larger glaciers. Although subglacial chemical denudation in the Karakoram Mountains is significant in carbon cycling at the continental scale, such carbonate dissolution probably contributes little to net consumption of carbon dioxide from the atmosphere.

### INTRODUCTION

Annual solute fluxes in rivers, per unit area of basin drained, are influenced both by lithology and the volumetric throughput of water or runoff. At the continental scale, mean annual solute flux increases with mean annual runoff (Walling & Webb 1983), and annual solute flux tends to be higher for rivers draining mountainous basins (Meybeck 1976). Although partial pressure of atmospheric carbon dioxide decreases with elevation, assuming equilibration of precipitation with the atmosphere, strong orographic increase in precipitation will lead to enhanced specific proton inputs to basins in mountainous areas. Where mineralogy of bedrock provides rapid reaction rates, and overall residence times are sufficiently long, dissolution involving such enhanced hydrogen ion throughputs should produce large solute yields in high mountain runoff. For example, according to Gibbs (1967) 45% of the dissolved material transported in the Amazon is contributed by Andean tributaries draining only 13% of the basin area. The Amazon in turn delivers an annual solute flux of 290 Mt from land to ocean (about 8.8% of the total global flux of dissolved material from 6.3% of the land surface), as estimated by Meybeck (1976).

Underlying lithology influences rates of reaction through constituent mineralogy and, through rock/soil-water contact time, the extent to which dissolution occurs. Solute fluxes in rivers tend to be high where basins

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overlie predominantly carbonate or evaporite terrain (e.g., Meybeck 1976). Carbonate substrates not only favour dissolution through rapid rates of reaction but also increase rock-water interaction through retention of water in aquifers. In mountainous regions, steep slopes, rapid runoff, often unreactive igneous and metamorphic bedrock and consequent thin soils might be expected to interact with low temperatures limiting rates of reaction to give generally low rates of chemical denudation (e.g., Drever & Zobrist 1992), despite high throughput of water. However, if headwater basins are glacierised solute flux will be enhanced by dissolution of the large quantities of finely abraded sediment with high surface area/mass ratios and freshly crushed surfaces produced by erosion of glacier subsoles, entrained and evacuated by flowing meltwater. Indeed, estimates of solute flux in meltwaters draining from small glacierised basins suggest cationic denudation rates in excess of the global mean (e.g., Collins 1983).

The Brahmaputra, Ganga and Indus Rivers deliver an estimated combined annual dissolved load of 219 Mt to the ocean (about 6.7% of the total global flux from 2.5% of the land surface) (Meybeck 1976), which suggests particularly high specific solute fluxes from basins in the Himalaya. A considerable proportion of this solute flux will arise in mountainous sub-basins over the tectonically active orogenic belt, in particular in those containing glaciers and/or underlain by susceptible substrates. Dissolution of suspended sediment will increase the importance to the overall solute flux of montane sub-basins, in which specific discharges can be enlarged by orographically enhanced seasonal precipitation to an order of magnitude or more above runoff from the whole basin. In rivers originating in the still tectonically active Himalayan and Karakoram Ranges, suspended sediment fluxes are considerably higher than in rivers draining from the other mountainous regions on Earth (Collins 1996, 1998). Had dams not been constructed, the great subcontinental rivers would deliver a combined 1.31 Gt of suspended sediment to the coast each year, about 7% of the total annual global sediment flux from the continents to the oceans (Milliman & Meade 1983, Milliman & Syvitski 1992). About 40% of the sediment load transported from the Karakoram and Himalayan Ranges to the plains by the Indus River is derived from glaciers in headwater basins (Collins 1996).

There are few reliable data from which solute fluxes in rivers draining glacierised basins in the Himalaya and Karakoram can be estimated, as is also the case for mountain ranges elsewhere. Hasnain & Thayyen (1999) collected two water samples a day between May and the end of October from Din Gad River which drains the small Dokriani Bamak glacierised basin in the Garhwal Himalaya. The gross cationic denudation rate was an exceptionally high  $4.16 \text{ eq km}^2 \text{ a}^{-1}$ , although how this value was derived from analyses of the samples was not disclosed. Measures of contemporary solute fluxes from mountain glaciers, and in particular from glaciers in the Himalayan arc, are required to document contemporary and long-term rates of surface denudational processes. Where erosion interacts with bedrock uplift, these rates are of particular interest because of imbalances between long-term rates of uplift and denudation which lead to development of mountainous relief. Well-constrained estimates of solute fluxes from Himalayan headwater basins will therefore be of value as indicators of modern rates of mountain chemical denudation, and of the contribution from active tectonic areas to land-ocean solute transfer.

Information concerning solute fluxes from Himalayan basins is also of interest with respect to the evaluation of possible linkages between tectonics, climate, glaciation, denudation and landscape development during the late Cenozoic. Uplift of the vast Himalaya-Tibetan plateau region may have led to cooling of global climate by perturbing atmospheric circulation (Ruddiman & others 1989) and, by greatly increasing monsoon precipitation (Schmitz 1987), raising rates of physical and chemical weathering of susceptible rocks in the active tectonic area (Raymo & others 1988). The latter increase could have lowered the atmospheric concentration of  $\text{CO}_2$  through increased consumption of the gas in weathering aluminosilicate minerals, and hence have contributed to the onset of glaciation in the Northern Hemisphere (e.g., Ruddiman 1997). An alternative view is that as global climate cooled in the late Cenozoic, enhanced erosion unloaded buoyant crust. Lowering of surface elevation would be offset by isostatic rebound as a result of the removal of debris by erosion, and climate further perturbed (Molnar & England 1990). Either way, growth of glaciers in the Himalayan region, through local elevation-precipitation interaction or through global cooling, will have affected the rate of denudation. Chemical weathering may have been enhanced, and removal of glacially eroded sediment may have increased dissolution in rivers. Critically, the question is whether climatic change can increase topographic relief (Whipple & others 1999). How much global rates of chemical weathering change between glacial and interglacial periods and what impact glaciers and icesheets have on solute fluxes remained unanswered questions. Interaction between glaciers,  $\text{CO}_2$  consumption by silicate weathering and atmospheric  $\text{CO}_2$  concentrations and hence climate over periods of  $10^3 - 10^5$  years remain unconstrained (Gibbs & Kump 1994, Kump & Alley 1994, Anderson & others 1996).

The aim of this paper is to provide detailed solute flux information, for a river draining from a basin containing a long valley glacier in the upper Indus basin, within the Karakoram Mountains, with a view to assessing the rate of contemporary subglacial chemical weathering. A large proportion of the valley glaciers in the Karakoram and Himalayan Ranges has dimensions considerably larger than those in other mountain regions for which measurements of solute flux are available.

## STUDY AREA

The basin containing Batura Glacier is located at about 37° N 75° E in the Karakoram Mountains, at the north-western end of the Himalayan chain (Fig. 1). The basin was selected for study as only one meltstream, the Batura River, drains from the glacier terminus. Also, the river can be gauged about 500 m from the glacier margin, by suspension of a current meter from the bridge carrying the Karakoram Highway (Fig. 2). Meltwaters

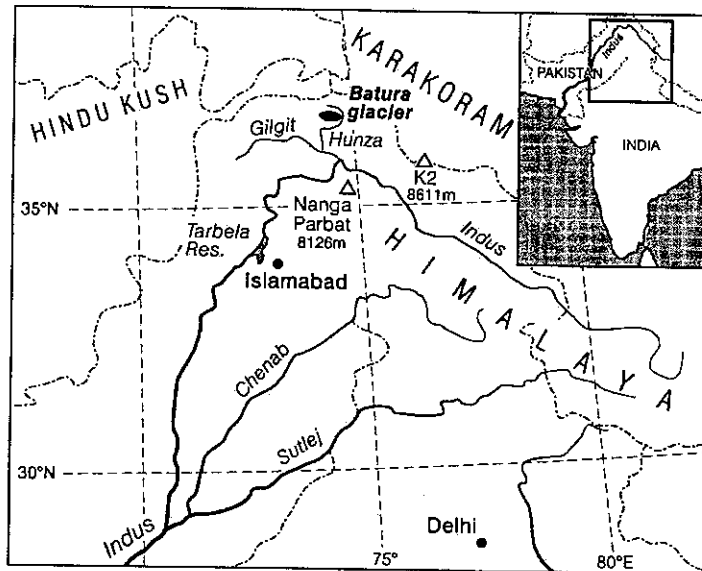


Figure 1. Location of Batura Glacier in the Hunza basin within the catchment of the upper Indus River in the Karakoram Mountains.

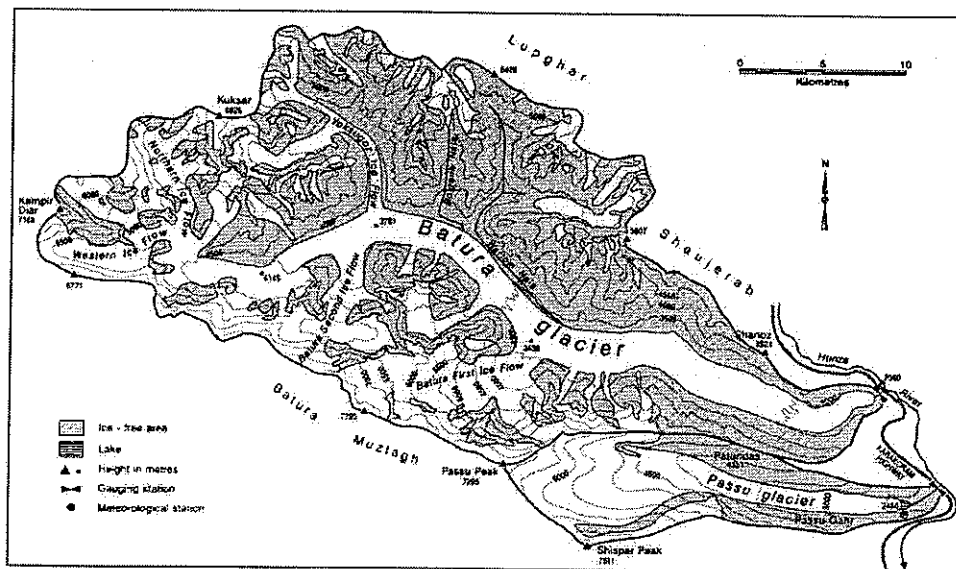


Figure 2. Map of Batura and Passu Glaciers showing locations of the gauging station on the Batura River at which measurements of discharge and electrical conductivity were obtained, and of the automatic weather station close to the terminus of Passu Glacier.

draining from the ~60 km-long glacier enter the Hunza River about 1 km from the portal, approximately 400 m downstream of Batura bridge. In turn, the Hunza basin is nested within the Gilgit and upper Indus River watersheds.

Batura basin extends between 2 567 m and 7 795 m a.s.l., encompassing an area of 649 km<sup>2</sup>, of which 56.3% (365 km<sup>2</sup>) is currently perennially covered with snow and ice. The basin is underlain by Gujhal dolomite, Passu slates and biotite-granodiorite (Searle 1991). Tectonically, the basin lies astride the north-south trending Nanga Parbat-Haramosh axis, a zone for which interpretation of fission-track ages and radiometric dates indicates rapid bedrock uplift of between 2 and  $\geq 5$  mm a<sup>-1</sup> and fluvial incision of between 2 and 12 mm a<sup>-1</sup> over the last 65 ka. (Burbank & others 1996). The Hunza valley is arid, the May 1974–April 1975 total precipitation being 97 mm, but the glacier is nourished by annual precipitation of more than 2 m at elevations above 5 000 m (Lanzhou Institute 1980), which occurs as snow. Almost all the runoff is derived from the glacierised area.

## ESTIMATING ANNUAL SOLUTE FLUX IN MELTWATERS

### Strategy

Continuous hydrograph records are necessary to characterise diurnal and seasonal variations of discharge from a glacierised basin. Concentrations of individual ionic species and total dissolved solids vary inversely and roughly in phase with meltwater discharge at the diurnal scale (e.g., Collins 1983). Additionally, concentration levels associated with a given discharge change during the ablation season. Combination of continuous hydrograph and chemograph records provides a reliable indication of temporal variation of solute flux (the product of instantaneous discharge and solute concentration). The sum of such products over a hydrological year provides a measure of total annual solute flux from a basin. Hourly flux resolution was used at Gornergletscher in the Swiss Alps by Collins (1983). Electrical conductivity (EC) readily provides a continuous chemograph, but, in order to permit estimation of actual ionic fluxes, requires calibration with determinations of individual ions in meltwater samples. These samples should be collected frequently, particularly during the ablation season. Where relatively infrequent sampling has to be used, samples should be collected throughout the range of observed values of EC and at intervals during the year.

Since more than 90% of the annual discharge from high mountain basins in the Karakoram Range occurs between May and October, the intention was to monitor stage and EC throughout an ablation season. Then a cationic concentration-EC rating curve was to be fitted from laboratory determinations of calcium, magnesium, potassium and sodium concentrations in meltwater samples, collected from as wide as possible a range of the annual EC variation. Ultimately, cationic flux was to be obtained from hourly paired values of discharge measurements and cationic concentrations taken from the rating curve.

### Meteorological variables

During most of the ablation season of 1990, screen air temperature, incoming global radiation and precipitation were recorded by an automatic weather station at an elevation of about 2 500 m a.s.l. on the right lateral Neoglacial moraine from which the terminus of Passu Glacier has now receded (Fig. 2). The site is located ~10 km downstream from Batura bridge, along the Hunza valley. Air temperatures at higher elevations were estimated using an assumed constant lapse rate, taken as 6.0 °C km<sup>-1</sup>.

### Discharge and electrical conductivity measurements

Meltwater stage was recorded continuously by a datalogger attached to a submerged pressure transmitter, secured in the turbulent fast-flowing river under Batura bridge. Gauging was undertaken occasionally during the season, encompassing a range of water depths. A current meter was suspended on a cable, together with a 100 kg sinker weight, from a derrick mounted on the roof of a Landrover. The vehicle was progressively repositioned on the bridge to permit a series of measurements of velocity, in verticals spaced at 2 m intervals across the width of the river, and at 20 cm depth increments. Stage usually increased during the time taken to complete a cycle of measurements, all of which were undertaken in daylight hours. Gauging was made difficult by both turbulence and the presence of standing waves. Discharge was calculated by the velocity-area method (British Standards Institution 1973), and related to the mid-range value of stage in estimating the stage-discharge rating relationship, from which hourly mean discharge was generated. The error in gauging must have been at least  $\pm 10$  per cent, and considerably greater at higher flows. EC was monitored using a WPA conductivity meter with a Sproule dip cell, the cell constant of which was obtained from calibration against 0.01 M KCl. Almost

continuous records were obtained between 9 April and 7 October 1990 at a site about 100 m upstream of Batura bridge and ~400 m from the glacier portal.

### CONCENTRATION OF CATIONS IN MELTWATER AND CATION-EC RATING RELATIONSHIPS

Samples of meltwater were collected at hourly intervals on several days with differing levels of flow in order to obtain wide coverage across the range of observed river EC, and hence discharge, in the ablation seasons of 1995 and 1998. Immediately after collection, samples were filtered through rinsed Whatman 0.45  $\mu\text{m}$  membranes. Samples were stored for up to 4 weeks in polyethylene bottles in darkness, in insulated containers, although temperatures rose to ambient levels in primitive field conditions. Subsequent storage until analysis was in a cold store at about 4 °C. Concentrations of  $\text{Ca}^{2+}$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$  and  $\text{Na}^+$  were determined by atomic absorption spectrophotometry and/or inductively coupled plasma analysis.

Rating relationships from which estimates of concentrations of individual cations and of the sum of determined cationic equivalents could be obtained from EC were fitted by linear regression. The goodness of fit for individual cations ( $r^2$  for  $\text{Ca}^{2+}$  0.72,  $\text{K}^+$  0.56,  $\text{Mg}^{2+}$  0.72 and  $\text{Na}^+$  0.74) was considerably improved for the sum of determined cationic equivalents ( $\Sigma\text{M}^+$ ) ( $r^2$  for  $\text{Ca}^{2+} + \text{K}^+ + \text{Mg}^{2+} + \text{Na}^+$  0.83). The best fit relationship between  $\Sigma\text{M}^+$  (in  $\text{meq L}^{-1}$ ) and EC was

$$\Sigma\text{M}^+ = 0.018 \text{ EC} - 0.038 \quad (1)$$

Despite the goodness of fit, measured sums of cationic equivalents deviated from those estimated using equation (1) by about  $\pm 5$  per cent at higher concentrations/EC values and up to  $\pm 20$  per cent at lower levels.

#### Cationic flux

Cationic flux ( $\text{eq s}^{-1}$ ) in meltwater draining from Batura Glacier was calculated as the product of hourly averages of cationic concentration ( $\Sigma\text{M}^+$ ) ( $\text{eq m}^{-3}$ ) and discharge ( $\text{m}^3 \text{ s}^{-1}$ ). As a result of inaccuracy in gauging discharge and error in estimating  $\Sigma\text{M}^+$  from EC, the accuracy of hourly cationic flux is probably at best  $\pm 15$  per cent. Daily total cationic transport was then derived from the 24 hourly means, except on those days on which fewer than 24 values were recorded, when the total was estimated from the mean flux obtained from the number of values available. For calculation of the total transport during the ablation season, estimates of daily total loads had to be interpolated on the few days within the otherwise complete record on which no data were recorded because of equipment failure. The mean of four total daily solute fluxes, those on the two days both before and after an interruption, was used in such interpolation.

### CLIMATIC CONDITIONS, MELTWATER DISCHARGE AND CATIONIC FLUX FROM BATURA GLACIER IN 1990

#### Seasonal variations in climatic variables and discharge

Cloud-induced reductions in incoming radiation punctuated the generally declining level of radiant energy input recorded at Passu from late June through October, leading to periods in which discharge was lower than flows occurring immediately before and after (Fig. 3). Increasing energy input in spring failed to produce rises in flow until early May and late June. Most of the glacier was observed to be covered with snow during that period, the albedo ensuring so that much of the available radiation was not utilised in melting through to early June, when the transient snowline rose significantly. Once snow cover is removed, the lower albedo of underlying ice leads to greatly increased specific yield of meltwater for the same energy input. The first steep rise in flow on 13 May followed a period of high radiation input, which was accompanied by a rapid temperature increase. The 0°C isotherm rose to almost 6000 m a.s.l., giving positive temperatures and hence melting conditions over about 80% of the basin area. Further steep rises in discharge, between 18 and 26 June, 29 June and 9 July, and 25 July and 1 August, coincided with observed rises of the transient snowline which increased bare ice area. Falling radiation input for melting after the solstice appears to have been offset by sensible heat during periods with warm air temperatures. From early August, runoff tracked energy input downwards. Any further expansion in area of ice exposed through continuing snowline ascent would have been unlikely to be sufficient to have an impact on overall ablation.

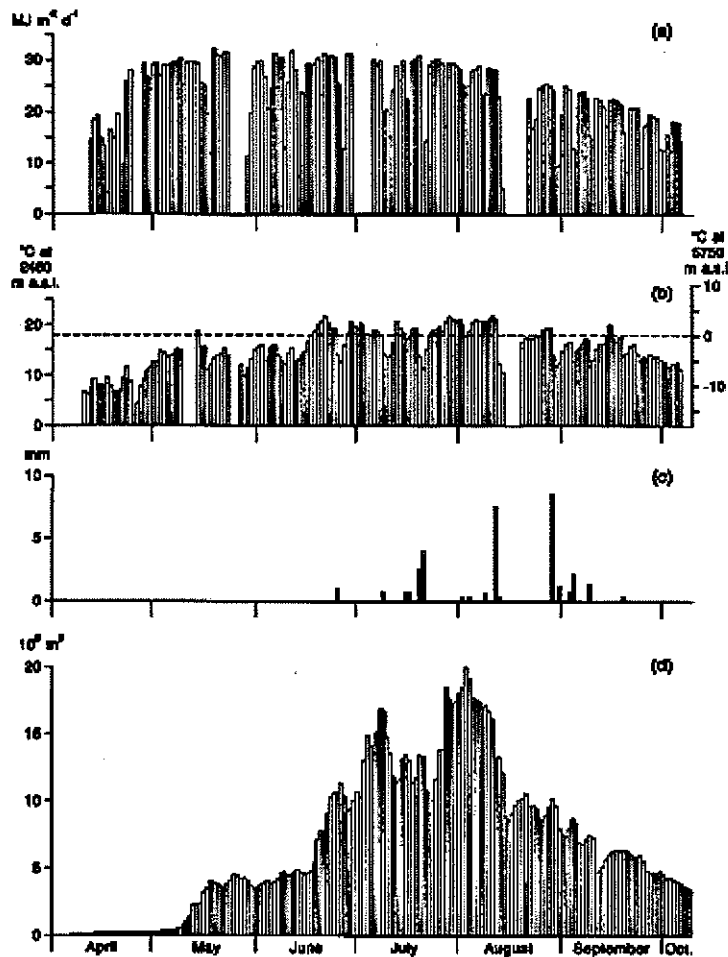


Figure 3. Seasonal variations of (a) daily total incoming radiation, (b) daily mean air temperature and (c) daily total precipitation recorded close to the terminus of Passu Glacier, and of (d) daily total discharge from Batura Glacier between April and early October 1990. The zero-degree level at 5450 m is roughly equivalent to a temperature of 180 Celsius at 2450 m a.s.l.

Principal precipitation events occurred on 21–22 July, 14–15 and 30 August. These events were associated with subdued temperatures and meltwater discharge was depressed (Fig. 3). On each occasion, reduced flow persisted for several days before recovery. Precipitation occurred as snow above about 4 500 m, even small quantities at lower elevations raising albedo and reducing the area of ice available for ablation. This effect was greatest in the mid-August event when the bare ice area was at a maximum.

#### Temporal variations of EC and discharge

In April, discharge showed minimal diurnal fluctuations based on an overall stable level of less than  $5 \text{ m}^3 \text{ s}^{-1}$  (Fig. 4). These variations were amplified in the accompanying inverse diurnal oscillations in EC, which were superimposed on a generally downward trend from  $\sim 140$  to  $\sim 70 \mu\text{S cm}^{-1}$ . Rising discharge in mid-May increased the diurnal range of flow fluctuation but damped the amplitude of diurnal EC fluctuation. The general level of EC remained above  $50 \mu\text{S cm}^{-1}$ . Discharge increased slightly and EC reduced marginally to mid-June. Both general level of EC and the range of diurnal variation were reduced as discharge sharply increased from 18 June. The highest discharges in the season to date on 9 July ( $>200 \text{ m}^3 \text{ s}^{-1}$ ) again reduced EC. EC recovered to a peak of  $75 \mu\text{S cm}^{-1}$  with widening diurnal range as discharge was reduced by cool cloudy conditions on 21–22 July. The final step increase in discharge, in late July, made little impact on EC which reached a minimum on 12 August. Perturbed by periods of increased/decreased flow which lowered/raised EC respectively, discharge then generally declined to the end of the observation period as EC increased, diurnal EC range widening through September.

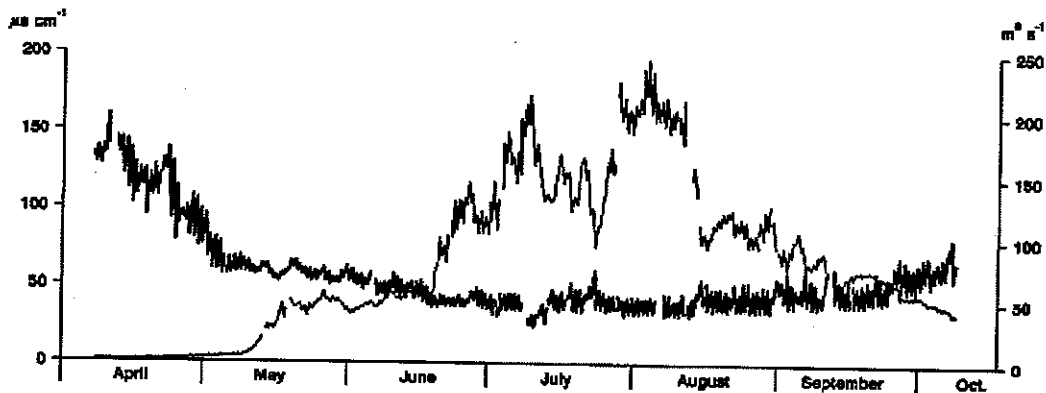


Figure 4. Hourly variations of electrical conductivity (thick) and discharge (thin) of meltwaters draining from Batura Glacier between April and early October 1990.

### Cationic flux and discharge

The pattern of peaks and troughs of cationic flux mimicked that of discharge (Fig. 5).  $\Sigma\text{M}^+$  increased in parallel with the first rise in discharge in May, above minimal winter levels. Subsequently, each pulse of rising and falling discharge was tracked by cationic flux. Each successive season to date peak discharge period produced a season to date cationic flux maximum. The highest daily totals of cation transport ( $>12 \text{ Meq day}^{-1}$ ) occurred during the period of greatest discharge in late-July – early-August. At the daily level, low levels of EC/solute concentrations were offset to an extent by the volume of meltwater discharged. Although total daily cationic transport increased with daily total flow, the rate of enhancement with discharge declined towards higher discharge levels (Fig. 6).

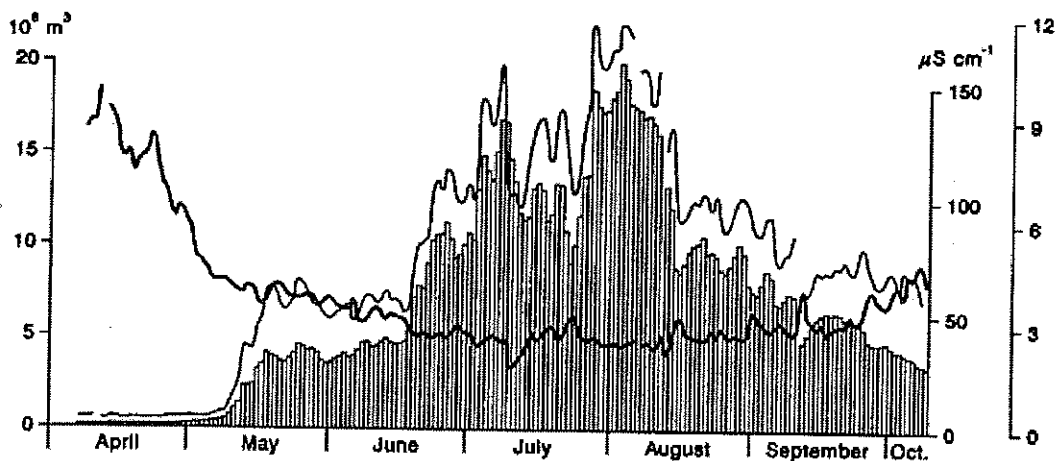


Figure 5. Seasonal variations of daily mean electrical conductivity (thick), daily total cationic flux (thin) and daily total discharge (columns) from Batura Glacier during the ablation season of 1990.

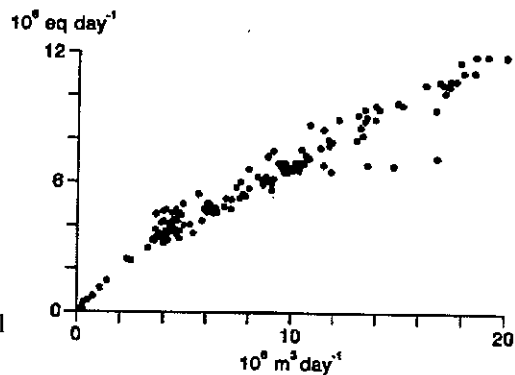


Figure 6. Total daily cation flux as a function of daily total meltwater discharge in the Batura River, 1990.

## ANNUAL TOTAL MELT WATER AND SOLUTE FLUXES FROM BATURA GLACIER

Total meltwater discharge from Batura Glacier recorded between April and October in 1990 was 1.25 km<sup>3</sup>. In 1974, the only previous year in which discharge was measured throughout the runoff cycle, about 85% of the total annual flow from Batura Glacier occurred between May and September (Lanzhou Institute 1980). Hence, in 1990, the total annual January–December discharge can be estimated as 1.25/0.85 = 1.47 km<sup>3</sup> (runoff of 2.265 m), considerably greater (by 58%) than the annual flow of 0.93 km<sup>3</sup> (1.354 m) measured in 1974. Runoff from the basin of Batura Glacier contributes ~10% of the total annual flow of the Hunza River at the gauge at Danyore Bridge, immediately upstream of the confluence with the Gilgit River, from 4.9% of the area (Collins 1996). The remainder is largely derived from the other glaciers in the Hunza basin. Total annual flows of the Hunza were 8.99 km<sup>3</sup> (0.681 m) and 11.92 km<sup>3</sup> (0.903 m) in 1974 and 1990 respectively, the latter being 33% higher than the former. The discrepancy between 33 and 58% is consistent with likely error in the accuracy of gauging. In 1990, total annual discharge of the Hunza River was about 11% above the 1967–1991 period mean.

Total cationic flux during the measurement period in 1990 was 927.008 x 10<sup>6</sup> eq. Annual total flux would have been higher, as a result of solute transport remaining above minimal winter (December/January – April) background levels during recession flow in October–November. Assuming that the winter 15% of total discharge transports a conservatively estimated 10% of the total annual cationic flux, total flux from Batura Glacier would have been 1 030.009 x 10<sup>6</sup> eq, or 1.587 eq m<sup>-2</sup> a<sup>-1</sup>. Because of the error in gauging the discharge, and errors arising from the use of the cation-EC rating relationship, the true annual gross cationic flux probably lies in the range 875.5 – 1 184.0 x 10<sup>6</sup> eq a<sup>-1</sup> (i.e., 1 030 ± 15 per cent). The lower slopes forming the ice-free portion of the basin receive little precipitation, so it is likely that almost all of the solute was acquired from the 60% of the basin beneath Batura Glacier itself. This represents a probable glacial yield of about 2.64 ± 0.40 eq m<sup>-2</sup> a<sup>-1</sup>. As the valleys are arid, and almost all the runoff is derived from glaciers, glacial acquisition of solute will dominate cationic fluxes in headwater tributaries of the Indus River in the Karakoram Mountains. The fluxes estimated here are slightly higher than initial estimates provided for Batura Glacier by Collins & others (1996).

## DISCUSSION

Using the same technique, a gross cationic flux of 0.478 eq m<sup>-2</sup> a<sup>-1</sup> was estimated for the 83% ice-covered, 82 km<sup>2</sup> basin of Gornergletscher in the Pennine Alps, Switzerland in 1978/1979 (Collins 1983). Runoff from Gornergletscher was 1.336 m in that year, low by comparison with the long term average for that basin as a result of the relatively cool summer in 1979. Gornergletscher basin lies on a substrate of granitic, gneissic and other metamorphic rocks. Annual total cationic flux from Gornergletscher is considerably lower than from Batura Glacier as indicated in Table 1. Nevertheless, both Gornergletscher and Batura Glacier yield cation fluxes higher than the average for the continents (0.390 eq m<sup>-2</sup> a<sup>-1</sup> according to Livingstone (1963). Reactive carbonate lithology and higher water flux, both individually and together, might be expected to enhance cationic flux from Batura Glacier by comparison with Gornergletscher.

Estimates of chemical denudation in other partially glacierised basins in a variety of settings were reviewed by Anderson & others (1997). Whilst also indicating cationic fluxes above the continental average, estimates for other glacierised basins were usually based on less adequate temporal characterisation of solute concentration than employed at Batura Glacier and Gornergletscher. Based on 2 samples a day and using a rating curve between concentration and discharge, Sharp & others (1995) estimated cationic fluxes of 0.64 eq m<sup>-2</sup> a<sup>-1</sup> in 1.71 m of runoff in 1989 and 0.69 eq m<sup>-2</sup> a<sup>-1</sup> in 2.31 m in 1990 from the 54% glacierised, 11.7 km<sup>2</sup> basin containing

**Table 1. Annual cationic fluxes from the basins of Batura Glacier, Karakoram Mountains and Gornergletscher, Pennine Alps.**

	Area (km <sup>2</sup> )	Period	Runoff (m a <sup>-1</sup> )	Gross cationic flux (eq km <sup>-2</sup> a <sup>-1</sup> )
Batura Glacier				
Basin	649	IV-X/1990	1.95	1.59 ± 0.24
Glacier	365			2.64 ± 0.40
Gornergletscher				
Basin	82	XI/1978-X/1979	1.34	0.48 ± 0.07
Glacier	69			



Haut Glacier d'Arolla, Pennine Alps, Switzerland. Reynolds & Johnson (1972) fitted a sine curve to analyses of 12 meltwater samples to generate an estimate of cation yield of  $0.93 \text{ eq m}^{-2} \text{ a}^{-1}$  in 3.28 m of runoff from the 50% glacierised, 6.1  $\text{km}^2$  basin of South Cascade Glacier, northern Cascade Mountains, in the western cordillera of North America. The annual cationic flux from Batura basin lies at the top end of the global range of reasonably reliable estimates of chemical denudation rates for what are smaller glacierised basins elsewhere.

Atmospheric input of cations in precipitation accounted for roughly 5% of the gross cationic flux in meltwaters draining from Gornegletscher (Collins 1983). Analyses of the sodium content of snow at elevations between 4 630 and 5 450 m a.s.l. on Biafo Glacier ( $36^\circ \text{ N } 76^\circ \text{ E}$ ) in the central Karakoram Mountains by Wake (1989) indicate  $\text{Na}^+$  concentrations in the range of 1-5% of those found in meltwaters draining from Batura Glacier. Much of the snow accumulates in winter from depressions steered by westerly winds under the subtropical jetstream, and hence distance from marine sources of aerosols over the Atlantic Ocean or Mediterranean Sea will probably result in generally low atmospheric cationic input to Karakoram glacial systems. Hence in both the European Alps and Karakoram Himalaya net cationic fluxes from glacierised basins probably approach gross levels.

Transport of large quantities of freshly abraded fine rock flour in high concentrations in large quantities of meltwater draining from mountain glaciers promotes subglacial chemical weathering. Suspended sediment flux in meltwaters draining from Batura Glacier during the measurement period in 1990 was  $6.086 \pm 10\%$   $\text{kt km}^{-2} \text{ a}^{-1}$  (Collins 1998). Assuming, not unreasonably in the near absence of precipitation on and of runoff from ice-free slopes, that the sediment was derived entirely and uniformly from beneath the glacier-covered area, specific suspended sediment yield from the subsole of Batura Glacier was  $10.144 \pm 10\%$   $\text{kt km}^{-2} \text{ a}^{-1}$ . Both flux and range of concentration of finely divided sediment are higher in the Batura River than in the Gornera River which drains Gornegletscher and transports between 0.882 and 1.666  $\text{kt km}^{-2}$  of sediment each year (Collins 1991). However, sediment content will promote chemical weathering of minerals in transit in meltwaters, both beneath and beyond the portals of the two glaciers. Sediment flux events from Batura Glacier occurred in 1990 on each occasion discharge exceeded levels not previously reached in the measurement period (Collins 1998). The initial sediment flux pulse occurred between 11 and 18 May, followed by further pulses between 18 and 26 June, in early July, late July and early August. Each sediment flux event, until early August, was associated with one of the significant increases of both meltwater discharge and cationic flux shown in Figure 5.

Solute flux in meltwaters appears therefore to be determined by interactions between mineral dissolution kinetics, sediment concentration, and contact time between sediment and meltwater, which all influence solute concentration, and discharge. As contact time depends on meltwater transit time through subglacial hydrological pathways, glacier dimensions will presumably also influence solute content of meltwaters. However, larger glaciers have greater meltwater discharges and hence higher flow velocities, which lessen transit times. Possible interactions amongst these variables are shown in Figure 7, based on the thought-experiment approach of Collins (1995a). In batch reactor experiments in which sediments of various mineralogies and particle sizes are

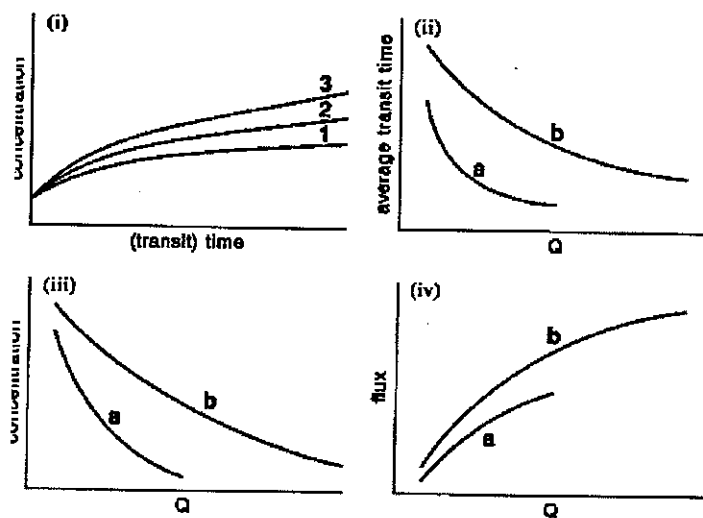


Figure 7. Relationships between variables which influence solute flux in rivers draining from (a) smaller or (b) larger glaciers. (i) curves of increase of solute concentration through time for reactions of minerals of differing reactivities ( $1 < 2 < 3$ ) with meltwater in either a batch reactor or during the transit time for a 'parcel' of meltwater and suspended sediment to pass through a subglacial pathway from point of entry to glacier portal; (ii) curves showing how average transit times for parcels of meltwater to pass through a glacier decline with increasing discharge; (iii) inverse relationships between solute concentration in meltwaters and discharge and (iv) curves indicating the declining rate at which solute flux increases with discharge.

added to water at temperatures of 0–1 °C, in a range of concentrations, solute concentration initially rises rapidly, rates of reaction declining as experiments proceed (Brown & others 1994, Collins 1995b). Carbonate mineralogy favours faster overall reaction rates than aluminosilicates. The former would be represented by curve 3 in Figure 7(i), the latter by curve 1. Increasing concentration of sediment of a given mineral also enhances reaction rate, i.e. the dissolution curve tends in the direction of curve 3. An open system with continued availability of CO<sub>2</sub> in solution through time would also tend towards curve 3. The increase in concentration of solute in a 'parcel' of meltwater during the time taken in transit from the point of first contact of meltwater with subglacial sediment at the base of a moulin shaft through the subglacial conduit system to the portal is also indicated by the curves shown in Figure 7(i).

Transit times for parcels of meltwater to pass subglacially, which determine the time available for reaction with sediment and hence the extent to which dissolution proceeds, are inversely related to discharge (e.g., Collins 1995). Overall transit time will also be influenced by basal drainage system configuration, state of seasonal development of the network and the general level of discharge. For a particular glacier, transit time will decrease with increasing discharge at both diurnal and seasonal timescales, as indicated by either of the curves a or b in Figure 7(ii). The longer a valley glacier and the higher concomitant overall discharge, the more curve b might be expected to apply. Coupling of rates of dissolution with transit times produces the inverse concentration-discharge relationship (Fig. 7(iii)). At lower flows, longer residence times allow concentration to rise, but at high discharges, reduced transit times limit the extent to which solute concentration in a parcel of meltwater can be raised. Presumably, for a given mineralogy, concentration will rise higher with longer traverses and hence extended residence times within larger glaciers (curve b in Fig. 7(iii)), higher discharges notwithstanding. As indicated in Figure 6 for the Batura River, solute flux increases with discharge albeit at a declining rate at higher discharges (Fig. 7(iv)). The shape of the flux-discharge curve depends on the extent to which volume of flow can offset the decline in solute concentration brought about by reducing transit/contact time. For the same substrate mineralogy, solute flux will probably be higher from larger and longer glaciers, which will have higher discharges (curve b, Fig. 7(iv)).

## CONCLUSION

Continuous monitoring of electrical conductivity indicated considerable seasonal variation in total dissolved solids concentration in the meltwaters draining from Batura Glacier, together with marked rhythmic diurnal variation throughout the ablation season. Estimates of total annual solute flux in rivers draining glacierised basins have to take into account this variability in solute content as well as that of discharge. Errors in estimating cationic fluxes in meltwater using the technique described in this paper arise largely from the use of a universal cation-EC rating relationship and from gauging turbulent meltwater rivers with fast-changing discharges. Uncertainty also results from extrapolation of cationic fluxes during periods of missing measurements. These errors will undoubtedly have influenced the calculation of cationic flux from Batura Glacier for 1990. However, such errors are unlikely to have been responsible for the flux from Batura Glacier reported here being so much higher than estimates for other glacierised basins, made using either the same experimental design in the case of Gornegletscher or less adequate methods elsewhere.

Carbonate lithology, sediment concentration in meltwater, annual total runoff and glacier length all favour a high cationic flux from Batura Glacier. The flux from Gornegletscher, substantially lower by comparison, is nonetheless greater than the continental average. Even the igneous and metamorphic substrate beneath Gornegletscher contains some carbonate (Bearth 1953) suggesting that at least some of the Ca<sup>2+</sup> in the Gornera meltwaters arises from that source. Extrapolation of the Batura Glacier cationic flux over all the glacierised area of the Karakoram headwaters points to a significant solute load being transported from the mountains by the Indus River. This load will be increased by continued reaction of glacially derived suspended sediment with meltwaters downstream of glacier portals in those valleys in which there are no lakes to prevent sustained suspension of sediment great distances away from subglacial sources. Even without the downstream dimension, glacial delivery of solutes to the high specific discharges that characterise the headwaters of the Indus River suggest an important role for glaciers in chemical weathering at the continental scale. Given the scale of contributions to the ocean by the major rivers with Himalayan sources, such fluxes are also significant at the global scale. Limestone lithology in the Karakoram Mountains enhances the contemporary solute flux not only from Batura Glacier but also from other glaciers in the range, and such dissolution of carbonate rocks is quantitatively important in global carbon cycling. However, being largely carbonate weathering, the contribution

of subglacial chemical activity in the Karakoram and Himalayan region to the net consumption of atmospheric carbon dioxide is probably small.

Tectonic uplift is likely to lead to an increase in solute flux from a rising mountain massif in the longer term. The rising land surface enhances precipitation orographically, and both discharge and solute flux increase. As a result of atmospheric temperature lapse rate with elevation, continuing uplift takes the land surface into progressively cooler zones where precipitation may occur as snow. Glaciers form in the higher areas where precipitation is also at a maximum. Glacial activity leads to fine sediment production by erosion, encouraging rapid mineral dissolution. High runoff then enhances solute flux. Should glaciers grow in size, through continuing uplift, the area of bed on which erosion can occur will enlarge. Even if sediment production continues at a constant specific rate, the quantity of fine material available for dissolution increases with glacier areal expansion. Larger glaciers have longer subglacial pathways, higher discharges and hence greater solute fluxes. Transport of glacial sediment from headwaters will probably continue to enhance solute fluxes in rivers draining high mountains for considerable distances downstream. A link between crustal and surficial processes is suggested here. However, whether, provided glaciers remain temperate, the rate of glacial erosion varies with glacier dimensions and whether glacial erosion rates are enhanced where bedrock is tectonically stressed have yet to be addressed.

The magnitudes of the cationic fluxes of between  $875.5 - 1\,184.0 \text{ Meq a}^{-1}$ ,  $1.35 - 1.83 \text{ eq km}^{-2} \text{ a}^{-1}$  from the entire Batura Glacier basin, and  $2.24 - 3.04 \text{ eq km}^{-2} \text{ a}^{-1}$  from Batura Glacier alone, both emphasise the importance of glaciers in chemical denudation in the Karakoram Mountains and point to potency of glaciers in global chemical weathering at present and in the past. Sustained measurement of solute fluxes in meltwaters draining glacierised basins at this and other locations across the Himalayan belt are now required in order to reduce dependency on data from only one glacier, to constrain year-to-year flux variability and to obtain estimates of solute fluxes in larger basins within which headwater glacierised basins are nested.

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